Some Open Issues on Rockfall Hazard Analysis in Fractured Rock Mass: Problems and Prospects

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To Prof. G. Barla:

I would also like to stress the need to check with due care the entire manuscript, including the references in the text and in the reference list and be sure that the guidelines on the web are carefully followed. In addition, have an overall check of the English editing.

Thank you very much for your suggestions: reference list has been carefully checked in terms of journals' abbreviation and alphabetical order. Moreover, an overall check of English editing has been performed.

Some open issues on rockfall hazard analysis in fractured rock mass: problems and prospects

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Abstract

Risk is part of every sector of engineering design. It is a consequence of the uncertainties connected with the cognitive boundaries and with the natural variability of the relevant variables. In soil and rock engineering, in particular, uncertainties are linked to geometrical and mechanical aspects and the model used for the problem schematization. While the uncertainties due to the cognitive gaps could be filled by improving the quality of numerical codes and measuring instruments, nothing can be done to remove the randomness of natural variables, except defining their variability with stochastic approaches. Probabilistic analyses represent a useful tool to run parametric analyses and to identify the more significant aspects of a given phenomenon: they can be used for a rational quantification and mitigation of risk. The connection between the cognitive level and the probability of failure is at the base of the determination of hazard, which is often quantified through the assignment of safety factors. But these factors suffer from conceptual limits, which can be only overcome by adopting mathematical techniques with sound bases, not so used up to now (Einstein et al. 2010; Brown 2012). The present paper describes the problems and the more reliable techniques used to quantify the uncertainties that characterize the large number of parameters that are involved in rock slope hazard assessment through a real case specifically related to rockfall. Limits of the existing approaches and future developments of the research are also provided.

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1. INTRODUCTION

Landslides are one of the most serious natural hazards in terms of victims and economic impact on the territory. To address the landslide problem, governmental agencies need to develop a better understanding of landslide hazard and to make rational decisions on allocation of funds for management of landslide risk. Rockfalls are among these phenomena, and represent one of the major causes of fatalities associated with landslides, due to the high energy and mobility of the involved rock blocks.

According to the most recent definitions, widely accepted at the international level (Fell et al. 2005, 2008), landslide hazard has to be characterized based on the frequency (or probability) of failure of the process and on its likelihood of impacting a given point of the slope with a given intensity. For rockfall problems, this means determining how often blocks detach from potentially unstable cliffs, what probability the blocks have of reaching a specific location on the slope surface, and the kinetic energy characterizing their trajectories.

The above process of analysis is dominated by uncertainty, concerning site characterization, material property evaluation, choice of constitutive, mathematical and numerical models, and static and dynamic stability analyses (van Westen et al. 2008). Furthermore the time factor and the spatial dimension of the area that can be involved in case of dynamic evolution of an instability process have to be considered as additional variables.

The designer has to answer questions such as: what happens when the slope suffers from a change in temperature, in water pressure or when it is subjected to an earthquake? Will some rock blocks fall, what are their volumes and their number? What will their paths and energies be? If these questions cannot be answered, the future cannot be forecast with certainty and the design will necessarily be subjected to a given level of uncertainty and thus of risk (Brown 2012). As it is not possible to deterministically define the problem (either because of the involved materials, or for the inevitable simplifications of the design approaches), any design concerning rock and soil engineering has a certain level of uncertainty and thus of risk that the designer has to evaluate and assume.

In this context, landslide hazard and landslide risk analyses have to be carried out, and the results can be expressed, either quantitatively (Rouiller et al. 1998; Guzzetti et al. 2002; Crosta and Agliardi 2003; Jaboyedoff et al. 2005; Lan et al. 2007) semi-quantitative or qualitatively (Mazzoccola and Hudson 1996; Bunce et al. 1997; Mölk et al. 2008).

Quantitative methods use numerical values or ranges of values and they express the risk, in quantitative terms, as the probability of a given level of loss and the associated uncertainties (Corominas et al. 2014). These methods can be deterministic/scenario-based (namely, focusing on a particular scenario) or probabilistic (taking into account the effect of all possible scenarios) (van Westen 2004).

Qualitative methods result in qualitative descriptions of risk in terms of high, moderate and low level (van Westen 2004, Lateltin et al. 2005). These are used when the hazard cannot be expressed in quantitative terms (e.g. the hazard information does not allow one to express the probability of occurrence, or it is not possible to estimate the magnitude), and/or when the vulnerability cannot be expressed quantitatively. No standard definitions exist for relative qualitative terms. Therefore, to avoid ambiguity, such terms are best defined with reference to quantitative values or ranges of value.

Semi-quantitative techniques express risk in terms of risk indices: these are numerical values, often ranging between 0 and 1, and they do not have a direct meaning of expected losses, but are merely relative indications of risk. Also in this case risk is expressed in a relative sense. Most of these methods use crude exponential patterns, and such a definition is not consistent with the definition of risk given in a quantitative analysis (Budetta and Nappi 2013).

However, quantitative estimates are not necessarily more accurate than qualitative estimations (Corominas et al. 2014) since the accuracy of an estimate does not depend on the use of numbers; rather, it depends on:

- whether the components of landslide hazard and landslide risk analyses have been appropriately considered;
- the availability, quality and reliability of required data.

Consequently, the decision whether to carry out and report the results of a landslide analysis quantitatively or qualitatively mainly depends on the quality and the quantity of available data.

Generally, for a large area where the quality and quantity of available data are too meager for quantitative analysis, a qualitative risk assessment may be more applicable; while for site specific slopes that are amenable to conventional limit equilibrium analysis, a detailed quantitative risk assessment should be carried out.

This paper focuses on the quantitative approach applied to rock fall, based on the rock fall failure geometry and frequency and on trajectory simulations. It applies a probabilistic analysis (Baecher and Christian 2003) to a case located in North West Italy (Rovenaud, Aosta Region, Italy); it analyzes the causes of geometrical and physico-mechanical uncertainties and it suggests some possible tools for their mitigation.

In particular, some solutions to obtain more high quality data are described, which could be treated with quantitative approaches through statistical analyses and advanced time-space analyses of instability phenomena. Finally the paper aims to show how improving quantity and quality of data and models would represent the first step for an accurate landslide hazard analysis.

2. UNCERTAINTY AND HAZARD ANALYSIS

Hazard is expressed as the probability that a particular dangerous phenomenon (a fragmented rockfall, in this case), occurs with a given intensity within a given period of time. Intensity and frequency are thus key parameters for evaluating rockfall hazard (Corominas et al. 2003; Jaboyedoff et al. 2005). However, rockfall hazard zoning is mostly performed using a relative hazard scale (van Westen 2004), which does not explicitly take into account time. In order to refine rockfall hazard, it is mandatory to use the frequency of events, or at least a qualitative estimate.

According to Jaboyedoff et al. (2005) the rockfall process can be divided into two parts: the first is the rock instability or failure in the source area and the second is the runout area at a distance. The hazard H(E, x) at a point x, for a given kinetic energy E, is given by the product of the rock-mass-failure mean probability or frequency, λ_f, (Bunce et al. 1997) and the probability of propagation up to x, P_p, (Guzzetti et al. 2002):

$$H(E,x) = \lambda_f \cdot P_p(E,x) \tag{1}$$

H(E) can be estimated for different energies; λ_f may depend on block volume (mass).

Moving to the analysis of the relation between hazard and risk, risk analysis aims to determine the probability that a specific hazard will cause harm, and it investigates the relationship between the frequency of damaging events and the intensity of their consequences. Vulnerability seeks to establish thresholds for the individual risk (i.e. the risk imposed by hazard to any identified individual) and the societal risk (i.e. the risk imposed by hazard on society) (Guzzetti 2004).

For example individual risk is widely discussed in Leroi et al. (2005): a review of individual life loss risk criteria proposed in recent years by different authors and authorities is also included, with values of risk/annum ranging from 10^{-6} to 10^{-3}. These authors highlight that there are no internationally accepted criteria for landslides and therefore it is necessary to develop tolerable loss of life criteria for each situation, taking into account of the legal framework of the country.

2.2 Sources of uncertainty

The nature of the uncertainties in rock engineering is extensively discussed in the literature (e.g. Wenner and Harrison 1996; Guo and Du 2007; Dubois and Guyonnet 2011; Bedi and Harrison 2013). Einstein and Baecher (1983), for example, classified the sources of uncertainty as:

- innate spatial and temporal variability;
- measurement errors (systematic or random);
- model uncertainty;
- load uncertainty;
- omissions.

Similarly, Baecher and Christian (2003) have schematized these sources of uncertainty in three categories, related to parameters, models and actions for mitigation.

Each different source of uncertainty has to be carefully analyzed and mathematically evaluated, taking first of all into account that the uncertainties could be epistemic, that is due to a lack of knowledge, or aleatory, that is linked to their intrinsic variability (Baecher and Christian 2003). The different types of uncertainty are characterized by different properties (Hudson 2013), which together contribute to the determination of the global uncertainty.

In this paper, in particular, uncertainties relevant to the slope have been considered after the application of sophisticated measurement tools. Statistical interpretation of the measurements have led to the quantification of the sampling error on relevant geometrical features that have an effect on the triggering and movement mechanisms of the blocks. Finally their effect on the results of rockfall simulations in terms of runout and energy are discussed in Section 3.3. The choice of relevant geometrical features has been made on the basis of in situ experimental results (Giani et al. 2004).

2.3 Probabilistic Analyses

The analysis of currently available procedures underlines that one of the most difficult challenges in rockfall hazard assessment is the estimate of time recurrence of events and associated magnitude (Corominas and Moya 2008).

Another source of uncertainty is related to size and shape of the unstable blocks, which are known to significantly influence trajectories down the slope and runout. In addition to the uncertainties involving the characteristics of the rockfall source area, further uncertainties affect the subsequent calculation steps in the production of a hazard map, namely the propagation of blocks, the applied hazard mapping techniques and how to merge all the available data, e.g. in a GIS environment, to obtain a map (van Westen et al. 1997; Corominas et al. 2003). As far as rockfall propagation is concerned, trajectory simulation codes may be very helpful tools for hazard assessment (Bunce et al. 1997; Guzzetti et al. 2002).

Probabilistic analyses provide an objective tool to quantify and model variability and uncertainty concerning geotechnical and geological parameters involved in rock slope stability. For example, starting from frequency distributions of cohesion and friction angle of a discontinuity plane and knowing how their variability influences slope stability, makes it possible to understand what the most probable mechanism of failure is and thus how to intervene. On the other hand, supposing that the discontinuity spacing within a rock mass is known, it is useful to define the variability of the block size that can detach, in order to evaluate the involved energies and, consequently, design protective measures. For this purpose, sensitivity analyses are carried out to identify the key-parameters, namely the ones which most influence the entire process.

In the following sections an example of statistical analyses applied to the different phases of rockfall are shown: in particular the relationship between the rock fall volume and its probability of failure is given for the particular case study, based on in situ surveys.

In the last section the results, obtained from the rock mass characterization, in terms of frequency distribution of volume of the detachable blocks, have been used as input data for a specific analysis carried out in order to study the rock fall propagation phase. In this case the CRSP code (Colorado Rockfall Simulation Program) (Pfeiffer and Bowen 1989) that is based on a statistical approach has been used to analyze how the shape and the dimension of the blocks can affect the results, and therefore the design of protection works.

3. HAZARD ASSESSMENT OF ROCK FALL PHENOMENA IN ROVENAUD

In the last 50 years, the International Society for Rock Mechanics (ISRM) has made significant efforts toward the comprehension of the hazard due to rock instability phenomena (Brown 2012). As a result, much more is known today on the triggering and propagation phases of instability events. However, other aspects, such as the space-and-time probability of such events, are far less known.

The triggering mechanism involves the study of the possible kinematics of the blocks and the consequent equilibrium analysis of possible removable blocks, whilst the movement mechanism involves the study of the block dynamics along the slope once the block is detached from the rock face. Rockfalls are landslide phenomena characterized by high mobility; as a consequence a run-out analysis that includes not only the source zones but the entire area that can be potentially involved needs to be performed. The presence of blocks at the base of the slope is proof of events that happened in the past; these blocks give significant information of the phenomenon both in terms of volume distribution of unstable blocks and of their trajectories.

In order to evaluate a rockfall hazard, the following steps are usually carried out:

- identification of the possible triggering area,
- determination of the probability distribution of the potentially unstable volumes (event magnitude),
- determination of the frequency of the instability phenomena,
- calculation of the trajectories for the determination of the distances and the involved kinetic energies.

In the following, the survey and calculation process necessary to assess a rock slope hazard will be shown through the description of the Rovenaud case study.

3.1 The Rovenaud case study

Figure 1 presents the rock block detachment zones that can be identified along a rock face located at Rovenaud, in the Grand Paradiso National Park (Valsavaranche, Aosta, Italy) and that hangs over a building housing the "Environmental Information Centre" of the park. Due to a recent reactivation of rockfall phenomena from this rock wall, a study aimed at making the site safe has become necessary. The rock slope consists of schists and calcareous mica schists, belonging to the Rovenaud unit, in contact with gneiss of the Grand Nomenon lithological unit (Fig. 2): a geological section through Valsavarenche, passing just south of the Center for Environmental Information, is shown in Figure 3. The base of the slope is characterized by an average inclination of 40° and by the presence of vegetated debris, and terraced zones made of dry stone walls; at about 300 m above the base of the slope, one can observe that the rock wall is 400 m wide and from 70 to 100 m high, dipping from 75° and 85°. Through the acquisition of terrestrial digital images a Digital Surface Model (DSM) of the slope has been created (Fig. 4) in order to perform both a no-contact discontinuity survey and rockfall simulations.

Fig. 1 Panoramic view of the rock face: source areas (orange), evident block detachment areas (red) and trajectories (green) are shown

Fig. 2 Part of the geological map on the area under investigation. The frame includes the case study area, and the red line corresponds to the geological section in Fig. 3. ZTG, BCC = Calcareous schist and marble tectonic breccia in carbonate cement; RVN = undifferentiated schist and calcareous-mica schist; RVNb = Blue / green ± silver metabasite to amphibole with subordinate quartz-albite; UID = Alluvial debris deposits fan of mixed genesis; UIDb2 =detrital-colluvial undifferentiated products (eluvio-colluvial deposit)

Fig. 3 Geological section (see Fig. 2) through Valsavarenche, passing just south of the Center for Environmental Information (Polino et al. to be published: Explicative Notes of Italian Geological Map scale 1:50000, Sheet 090 Aosta)

Fig. 4 View of the colored DSM of the slope, with indication of source area and considered section

The geomorphological structure of the area of interest, as well as that of the entire Valsavarenche and more generally of the Aosta Valley, is the result of the interaction between the endogenous processes, which resulted in the lifting of the alpine slopes, with exogenous processes related to glacial, fluvial, gravitational and avalanche dynamics. Remodeling by rivers, by the action of gravity, by avalanches or their combinations are widespread here, as indeed in all the alpine valleys.

Detachments of isolated blocks and block accumulation at the base of the slopes can be observed in this area; deposits of this type are extremely common and widely distributed in all units and in all the valleys, along the left side of Valsavarenche (Polino et al. to be published: Explicative Notes of Italian Geological Map scale 1:50000, Sheet 090 Aosta).

3.2 On-site characterization and determination of potentially unstable blocks

The on-site characterization at the mesoscale (slope) is always the first step in a stability study; in fact, the major aspect of rock slopes is the presence of planes of weakness (discontinuities) which, intersecting the rock define possible failure mechanisms. As can be noticed by the analysis of the rock slope represented in Figure 5, the movement of rock blocks originates at the intersection among the discontinuities that pre-exist and are ubiquitous within the rock mass. The identification of discontinuities and measurement of their properties (ISRM 1978) form the basis of many studies in rock mechanics. In particular, the geometrical characteristics of the joints (orientation, spacing and persistence) are generally obtained by a measuring tape and a geologic compass or by the use of new non-contact techniques (Ferrero et al. 2009). The hypothesis that the discontinuities are recurrent allows one to collect data in a certain area and extend them to the entire rock mass.

Fig. 5 Identification of the rock-fall triggering zone and of discontinuity patterns

The geostructural survey has been performed through the acquisition of terrestrial digital images and the photogrammetric reconstruction of a Digital Surface Model (DSM). The use of a software specifically developed for measuring plane orientations (Rockscan, Ferrero et al. 2009 – Fig. 6) made it possible to collect a large amount of high quality orientation data, which can be thus analyzed with statistical techniques (Fig. 7).

The procedure proposed by Umili et al. (2013) has been applied to the obtained DSM and a dataset composed of 10720 traces was obtained, ranging from 0.3 m to about 50 m. In particular, three main discontinuity sets were identified using the automatic cluster analysis, performed by means of the ISODATA algorithm (Ball and Hall 1965) (Fig. 8).

Fig. 6 Selection of discontinuity planes for automatic calculation of orientation with Rockscan

Fig. 7 Identification and mean planes orientation of the three main discontinuity sets (K1, K2, K3) and slope

Fig. 8 Rovenaud DSM and traces identified by CurvaTool (Umili et al. 2013); traces are colored in relation to the set to which they belong (red: set 1; green: set 2; yellow: set 3)

The selection of the trace length frequency distribution was based on research by Kulatilake et al. (1993, 2003), Zhang and Einstein (2000), Wu and Wang (2002), who proposed the negative exponential frequency distribution:

$$g(l) = \mu \cdot e^{-\mu l} \tag{2}$$

where l is the trace length variable from 0 to + ∞, the constant μ is defined as the reciprocal of the mean value of the traces sample (m_s):

$$\mu = 1/m_s \tag{3}$$

and the theoretical standard deviation σ of the negative exponential frequency distribution is defined as:

$$\sigma = 1/\mu \tag{4}$$

A rigorous method to evaluate the goodness of fit of a distribution on a sample is the chi-squared (χ^2) test, which states that:

- if $T > \chi^2_{\alpha,k-1}$ then the H0 hypothesis must be rejected;
- if $T \leq \chi^2_{\alpha,k-1}$ then the H0 hypothesis must be accepted; (5)

where α is the significance level of the test, k is the number of degrees of freedom and H0 hypothesis is "negative exponential distribution fits data". T is defined as:

$$T = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \tag{6}$$

where O_i is the i-th observed frequency and E_i is the i-th expected frequency.

Figure 9 shows that in the analyzed case this distribution actually fits the traces of the sampled data very well; this is confirmed also by the values in Table 1, in particular by the chi-squared goodness of fit test (5), which is always satisfied.

Figure 10 shows the comparison among the distributions obtained for each of the three discontinuity sets and for the global dataset.

Table 1 Mean and standard deviation values of the trace length samples for each discontinuity set and for the global sample and parameters of the associated frequency distribution

Fig. 9 Comparison between frequency distributions obtained from the theoretical formulation and from the global dataset

Fig. 10 Frequency distribution of the trace lengths for each discontinuity set and for global dataset

3.3 Scale effect as source of uncertainty

In order to consider the scale effect on trace length, the above global traces dataset has been gradually reduced by considering sampling area, that is the area in which traces to be considered must be contained, varying between 100% and 0.12% of the total surface S of the DSM (corresponding to about 38'700 m^2) (Fig. 11). Due to the elongated shape of the DSM we chose to center all the windows in the same point, approximately in the middle of the DSM, and reducing their area from the total surface down to the surface containing at least 20 traces. A trace length distribution was obtained for each sampling window (Fig. 12): the comparison among the different distributions highlights that the scale effect is actually present and it decreases by enlarging the sampling area.

The traces measured directly on the DSM were then used to calculate the mean trace length for each sampling window. The results are shown in Figure 13: as expected, the trend of mean trace length is asymptotic and a good approximation of the real value is reached for a sampling area of about 50% of the total surface S.

Fig. 11 Different observation windows for the survey of the size of the blocks

Fig. 12 Frequency distributions of traces obtained by varying the sampling area (the distribution for 63% S is almost coincident with that for 81% S, therefore it cannot be seen)

Fig. 13 Mean trace length value obtained by varying the sampling area s (expressed as a percentage of S): experimental values (black) are best fitted by the curve (red) expressed as $2.5 \cdot S^{0.04}$ ($R^2 = 0.91$)

In Figure 14 the frequency distribution of the normalized spacing is shown for different z size, of dataset K2: $z = x_s - m_{100\%}$ where $m_{100\%}$ is the spacing mean value of the global sample obtained considering the total surface S ($m_{100\%} = 2.08$ m, see Table 2) and x_s is a generic value of spacing belonging to the subsample obtained considering a sampling area s that is a percentage of S.

The dotted line that is used to connect peaks z(p) of the various curves shows that the mean value changes as a function of the sampling area and tends to a constant value above the 25% of the sample. As a consequence, a portion of the slope in which 25% of the whole sample can be surveyed can be considered as the REV (Representative Elementary Volume) of the rock mass. Below this value, the average spacing would be affected by the error due to the insufficient extension of the sampled area. The error that is due to the intrinsic randomness of the discontinuity set can also be reduced by sampling more traces (note how the distributions become narrower by increasing the sample) but not completely eliminated.

Fig. 14 Frequency distribution of normalized spacing z by varying the size of dataset of K2 spacing values: $z = x_s - m_{100\%}$ where $m_{100\%}$ is the spacing mean value of the global sample and x_s a generic value of spacing. Best fitting normal distribution curve for each considered subsample is represented; dotted line connects peaks z(p) of the various curves

Table 2 Mean and standard deviation values of spacing global sample and considered subsamples

3.4 Block volume

The knowledge of the discontinuity characteristics makes it possible to determine the distribution of the rock volumes that can detach from the wall. On the basis of the geometric data of the discontinuity families, it is then possible to evaluate the size (V_B) of the rock blocks. In the case of 3 discontinuity sets, for example, the following relation can be applied (Palmström 1996):

$$V_B = \frac{S_1 S_2 S_3}{\sin \gamma_{12} \sin \gamma_{23} \sin \gamma_{13}} \tag{7}$$

where S_1, S_2 e S_3 are the spacing of the three sets and γ_{12}, γ_{23}, γ_{13} the angles among the sets.

A Monte Carlo simulation, which takes into account the frequency distribution of the traces, allows one to determine the frequency distribution for a considered volume of block obtained from spacing data surveyed on the rock wall (Fig. 15).

Such distributions can be validated by means of a comparison with the frequency distribution of the volume of the rock blocks observed at the base of the slope. Figure 16 shows the location of the detached blocks that can be observed at the base of the slope: they are indicated with circles, whose size is proportional to the measured volume and whose color is a function of the falling date of the block.

Fig. 15 Comparison between the cumulative frequency curves of the rock blocks volume surveyed on the rock wall and at the slope base

Fig. 16 Location of the blocks surveyed (Quagliolo and Balestro 2013, personal communication), two considered sections for rockfall simulations (yellow lines) and colored points indicating volume and the falling date

Even if the duration of direct observation of the detachment phenomena lasted only thirty months, the volume frequency distribution of rock fall has been determined following a power law (Dussauge-Peisser et al. 2002; Picarelli et al. 2005; Hantz et al. 2003; Hantz 2011):

$$f(V) = a \cdot V^{-b} \tag{8}$$

where f(V) is the frequency of rock falls with a volume greater than V, *a* is a constant representing the annual frequency of blocks having a volume greater than 1 m^3 and *b* assumes a value characteristic of the site ranging between 0.4 and 0.7.

In Figure 17 the power law fitting the data obtained for the 39 blocks with a volume between 0.4 and 51.9 m^2 detached in the observation period is reported. The constants *a* and *b* have been estimated equal to 5 rock falls per year and to 0.55, respectively.

Fig. 17 Class of volume V vs. frequency in time f(V) obtained for the detached blocks in the observation period

The frequency curves of the volume of the blocks in the slope (not detached) as a function of the size of the observation window are shown in Figure 18. It can be noticed that the dimension of the window highly influences the estimated dimensions of the blocks (larger window, larger blocks). As a consequence, it emerges how important it is to carry out statistical analyses on windows whose size is larger than the REV, in order to prevent underestimations due to scale effects.

Fig. 18 Frequency curves of the volume of the blocks as the size of the observation window changes. The symbols W1, W2, W3, W4 and W5 refer to windows shown in Fig. 11

3.5 Analysis of the propagation phase

The analysis of the propagation phase is very important when evaluating the size of the areas that are involved in a given event. The type of calculation tools depends on the type of phenomenon to analyze.

The Lumped Mass methods (Piteau and Clayton 1976; Wu 1985; Bozzolo and Pamini 1986; Hungr and Evans 1988; Pfeiffer and Bowen 1989; Stevens 1998; Guzzetti et al. 2002; Spadari et al. 2013) fit well the study of rockfalls. These methods model the mass concentrated in points and solve the dynamic equations, taking into account sliding and bouncing phenomena.

The DEM methods (Cundall 1971) are appropriate for the study of interacting blocks having a moderate mobility and are therefore suitable to study, for example, large rockslides.

An example of results obtained with Rotomap (Geo&Soft), a tridimensional lumped mass model is presented in Figure 19. It refers to the study carried out for the Rovenaud site (see section 3.1) to identify the run-out paths and the deposition area of the blocks that detach from the rock face. These simulations allow one to draw curves identifying areas with the same percentage of stopping-blocks and can be used to validate the model by comparing the computed tracks with those surveyed on site (Fig. 20).

Since the main purpose of this paper is to understand how uncertainties can affect the modeling results, simulations of rock fall paths have been carried out using the CRSP (Pfeiffer and Bowen 1989) along four vertical sections (Fig. 16).

The coefficients used to simulate the bouncing and sliding phases of the rockfall path (R_N, R_T and S) have been calibrated by means of a back-analysis based on the observed detachment zones and stopping areas and in relation to the boulder volume (Table 3). The starting area has been assumed to be an overall vertical outcropping rock mass. Along each vertical section the analyses have been performed by varying the shape (sphere or disk) and the dimension of the blocks. Blocks considered in these simulations have a volume of 0.5, 1.5, 6, 10 and 16 m^3 corresponding respectively to 35, 50, 80, 90 and 95% of the cumulative frequency curve obtained for the blocks surveyed at the slope base (Fig. 15).

The code statistically analyses the kinetic features of the blocks run out (trajectory, velocity, total kinetic energy, taking into account both translational and rotational components), simulating the paths travelled by several blocks by randomly varying the local slope angle at the impact point.

Along each vertical section and for each shape and volume of the blocks, the run out of 1000 boulders has been simulated. The results have been statistically analyzed, obtaining the maximum bouncing height and kinetic energy assumed by the blocks in relation to a point located at the base of the slope where a retaining structure is forecasted.

Fig. 19 Rovenaud study site. Computed paths of the falling rock blocks (Quagliolo and Balestro 2013, personal communication)

Fig. 20 Rovenaud study site. Curves of equal percentage of stopping-blocks obtained from simulation compared with the position of the blocks surveyed on-site (colored circles) (Quagliolo and Balestro 2013, personal communication)

Table 3 Tangential (R_T) and normal (R_N) restitution coefficients and surface roughness parameter S used in CRSP code to analyze the rock fall run out

Figure 21 shows the maximum bouncing height of the blocks in correspondence to the analyzed point, along the four analyzed vertical sections and by varying the shape (sphere and disk) and the volume of the boulders. In the diagram, the values of the bouncing height are normalized with respect to the radius obtained by considering the five spherical block volumes. Results show that the maximum bouncing height is not affected by the block shape, while, on the contrary, it strongly decreases as the volume increases, accordingly to the R_N and R_T reduction, but not proportionally to their values.

Figure 22 shows the relationship between the total kinetic energy and the volume of the blocks. The total kinetic energy includes both the translational and rotational components of the motion and its value is normalized with respect to the volume of the block (specific kinetic energy). It is possible to see how the specific kinetic energy decreases as the volume increases both for spherical and discoidal blocks.

In order to be able to stop a block at a certain point along its path, the structural capacity of the rockfall protection system must be defined on the basis of the maximum estimated block size, but its dimension must be designed considering the trajectory (in particular, the maximum bouncing height) of the smaller ones.

Fig. 21 Boulder volume vs. normalized maximum height obtained in the analyzed point located at the base of the slope along the four analyzed vertical sections

Fig. 22 Boulder volume vs. total kinetic energy per unit of volume obtained in the analyzed point located at the base of the slope along the four analyzed vertical sections

4. CONCLUSIONS

Hazard is related to the existence of several uncertainty sources, which make it difficult to know the evolution of a given phenomenon with absolute certainty. This generic statement is particularly true in soil- and rock-mechanics. The lack of knowledge can be partially accommodated through the application of advanced techniques. In order to reduce epistemic uncertainties models can be very sophisticated and realistic, particularly if they are calibrated through comparisons with very reliable monitoring measurements. However, an insurmountable aleatory variability remains and makes it necessary to run statistical analyses that allow one to quantify the effect of the variability and thus the hazard caused by rock slopes.

The present work has used a case study to describe how the scientific community is working to improve the quality of measurement and computational tools, which may contribute to a more reliable prediction of the hazard related to rockfall. The scale effect on discontinuity trace length and block volume has been determined and its influence on rockfall simulations has been shown, in order to highlight that a proper rockfall hazard mapping must contemplate uncertainties.

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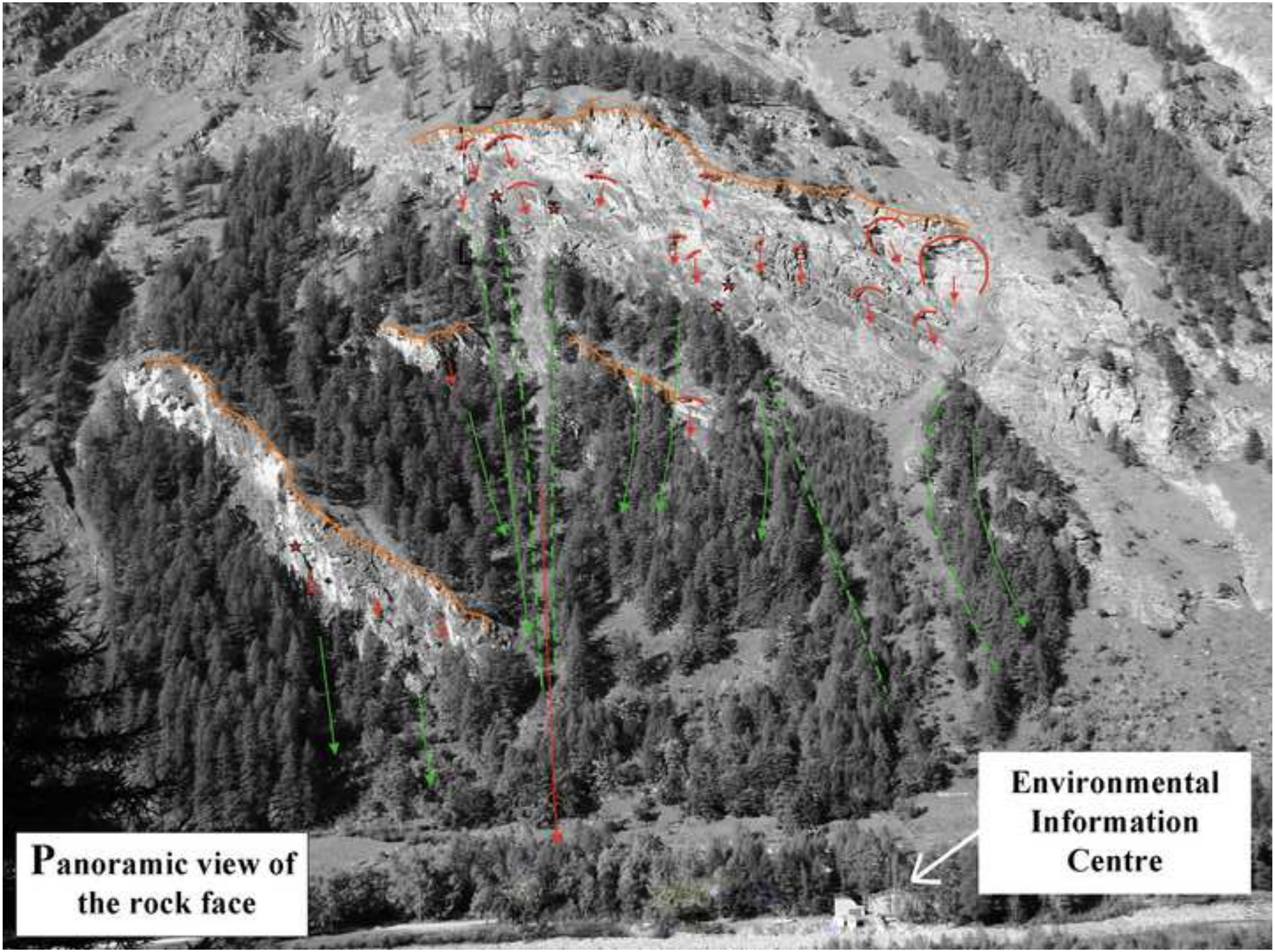

Figure 2

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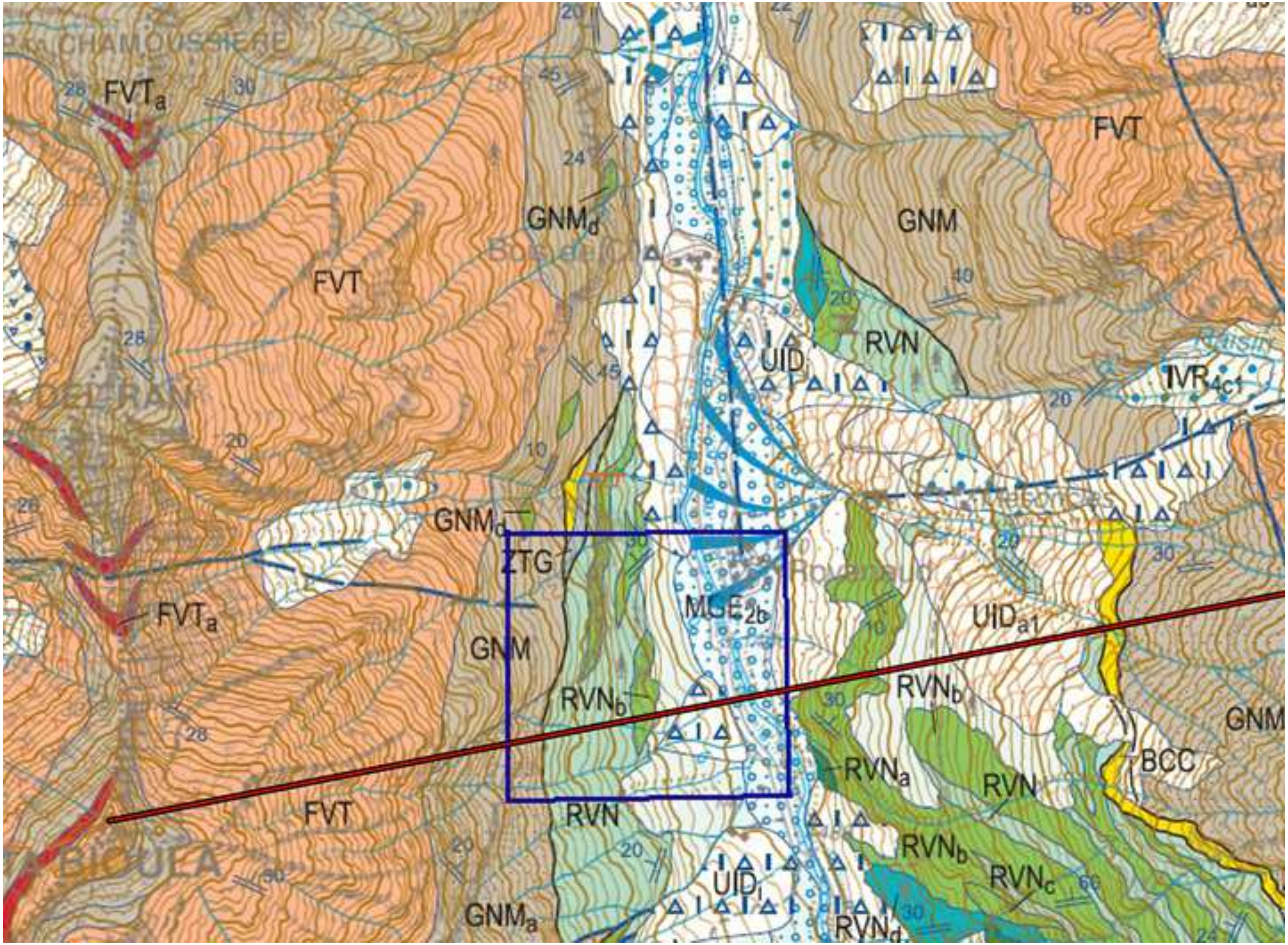

Figure 3

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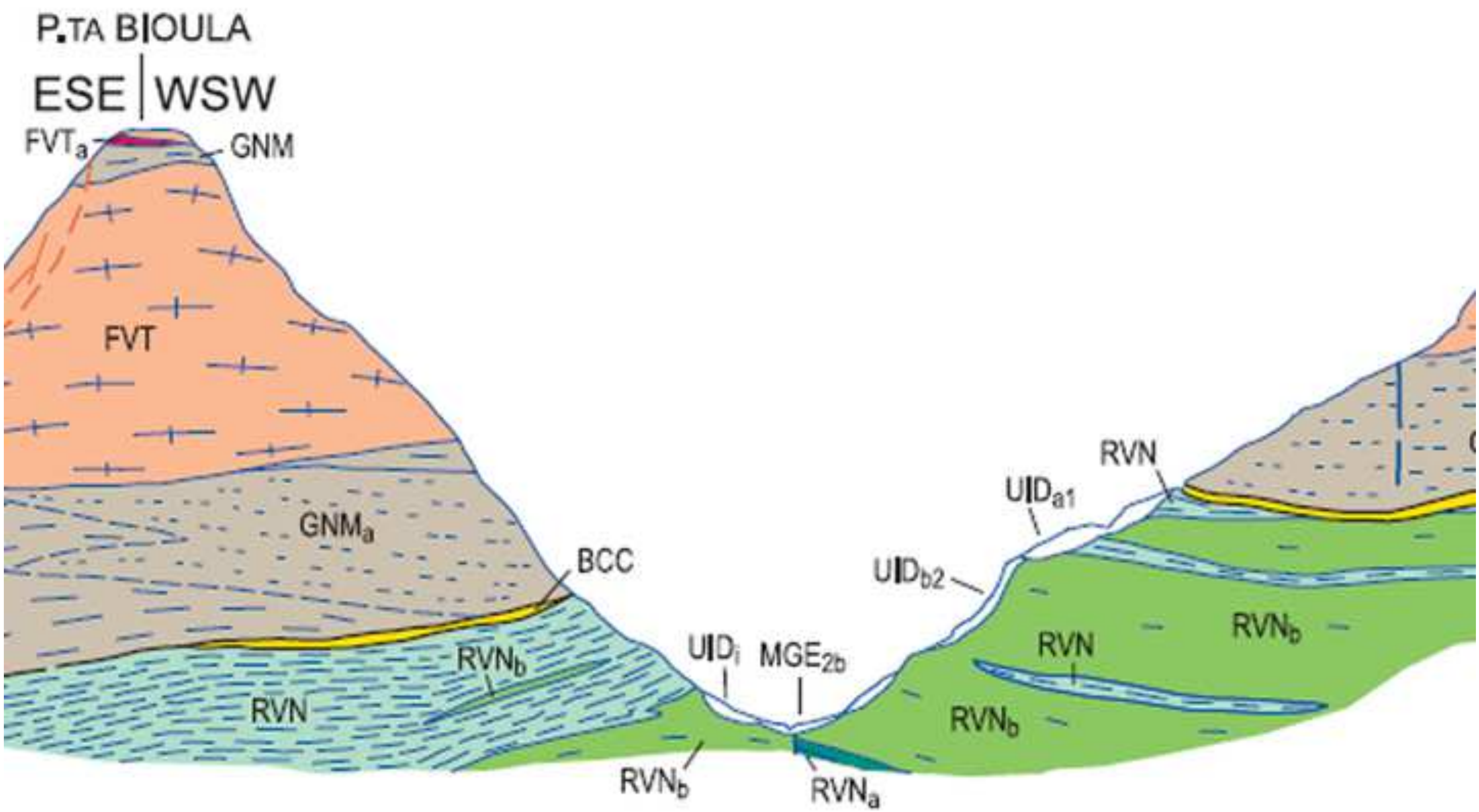

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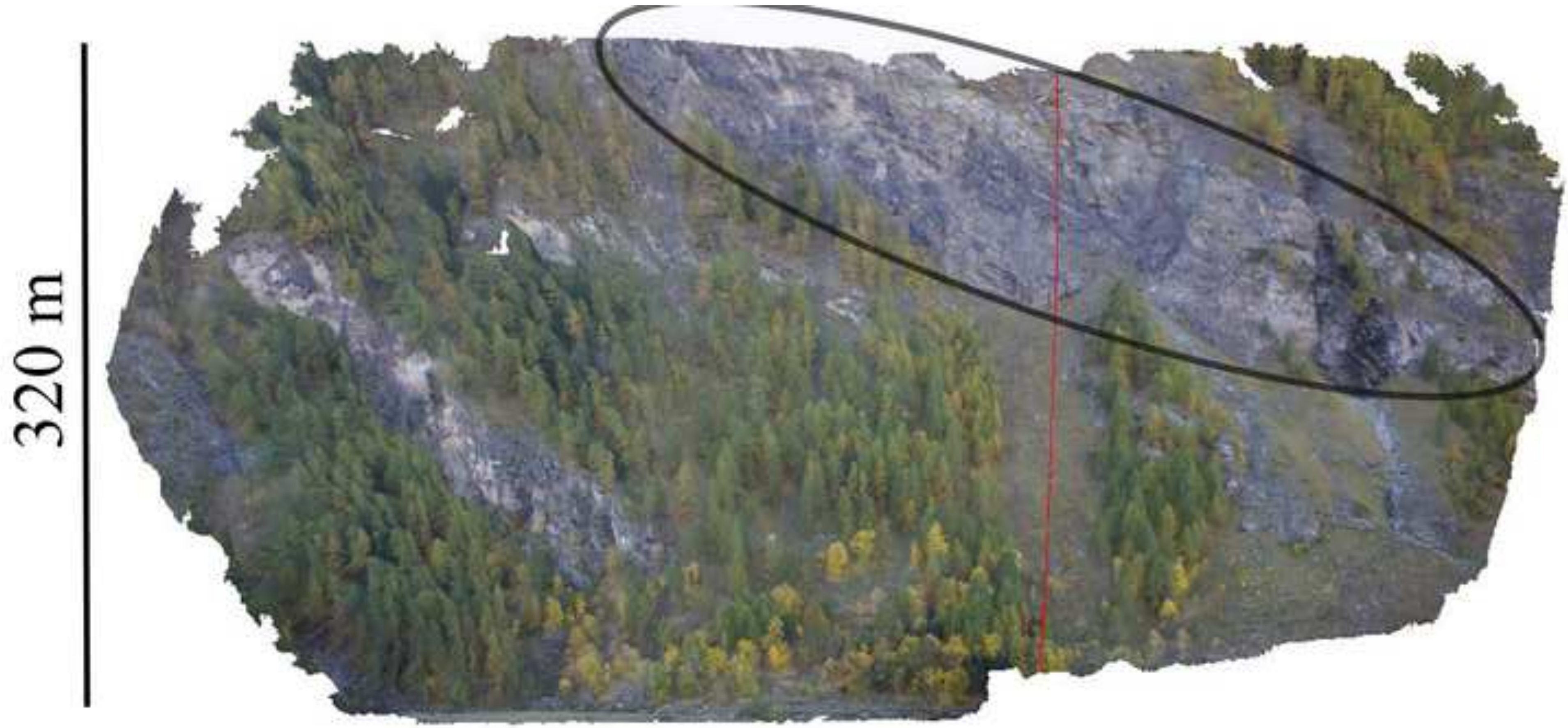

Figure 5

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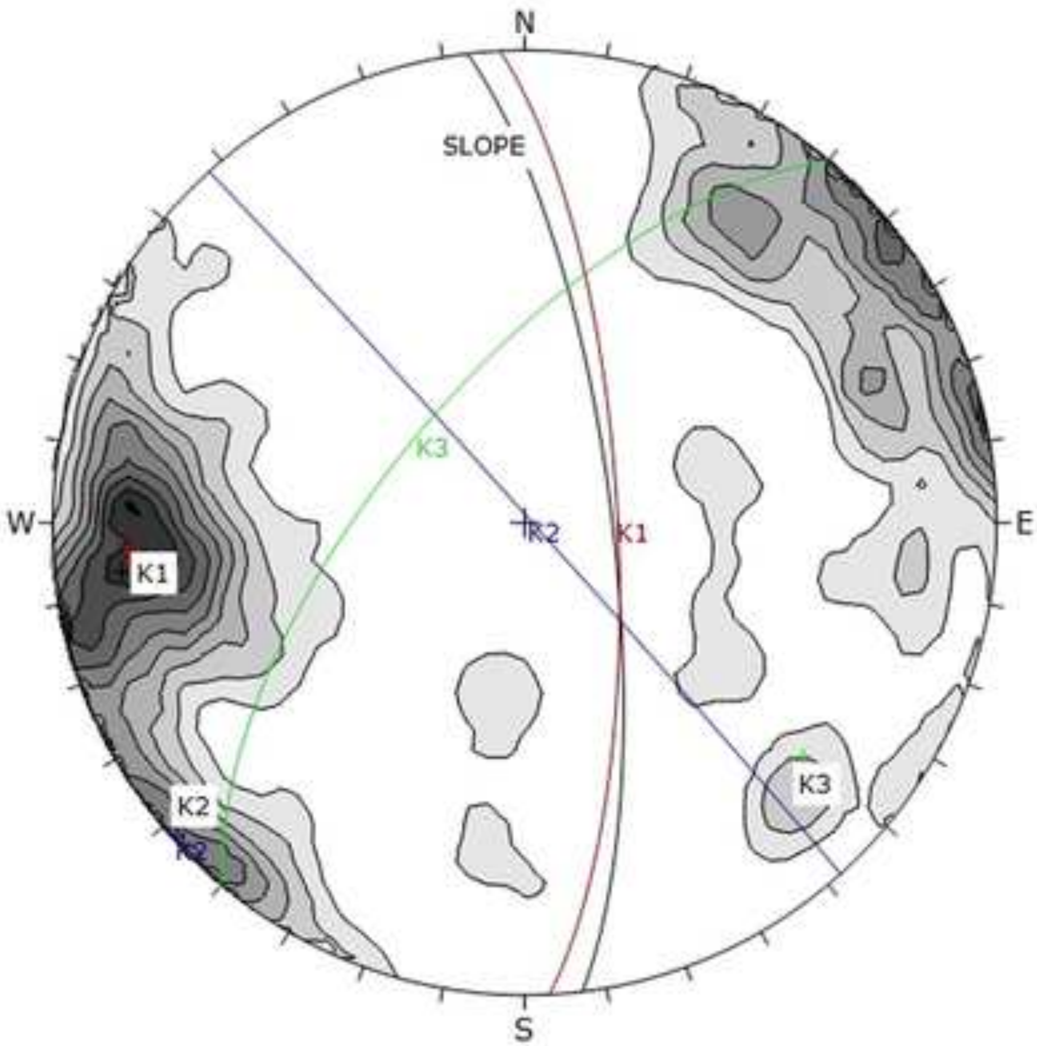

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Mean Set Planes				
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3m		66	310	K3
4m		74	87	K1

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Vector Count	235 (235 Entries)
Hemisphere	Lower
Projection	Equal Area

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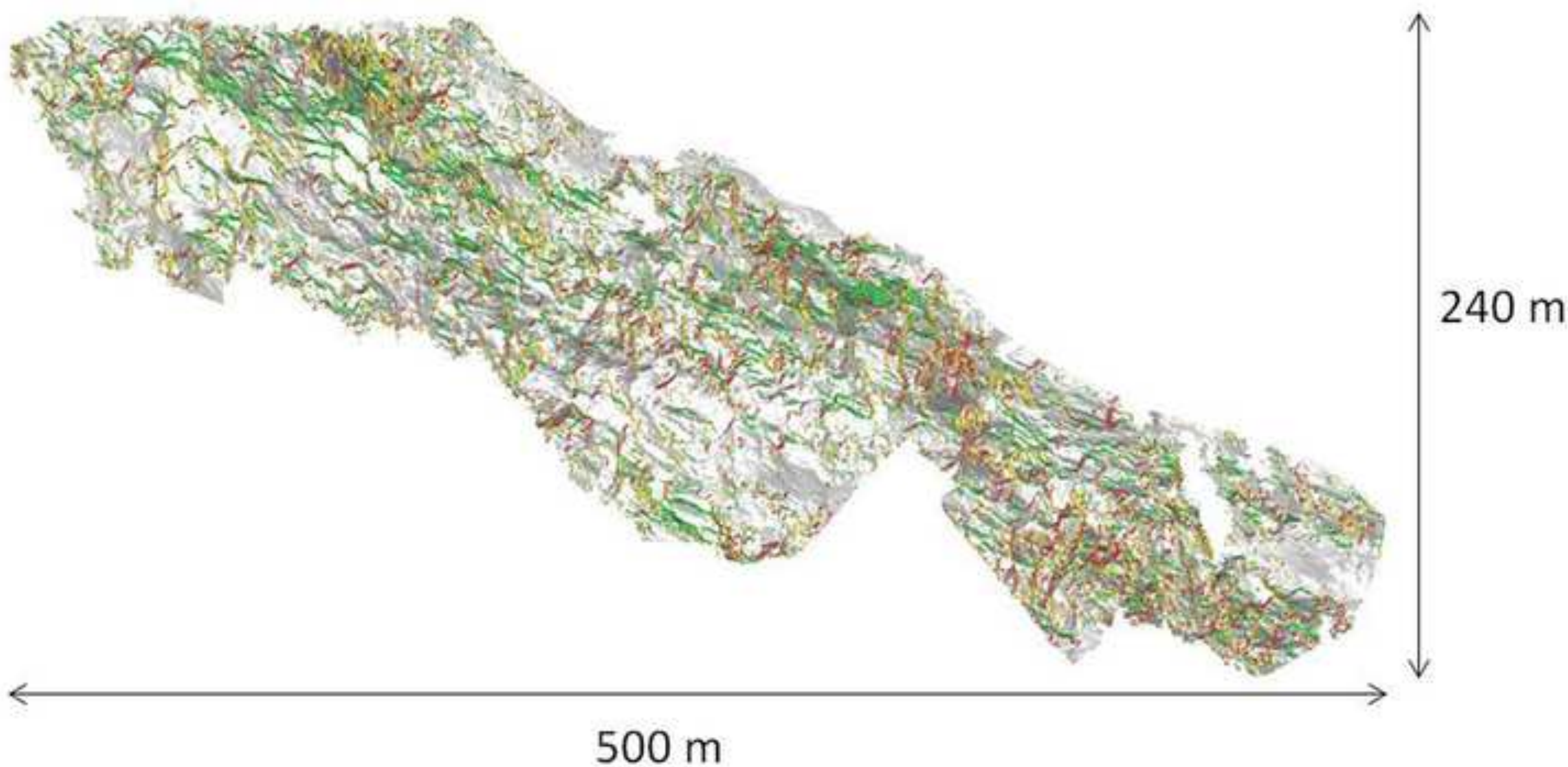

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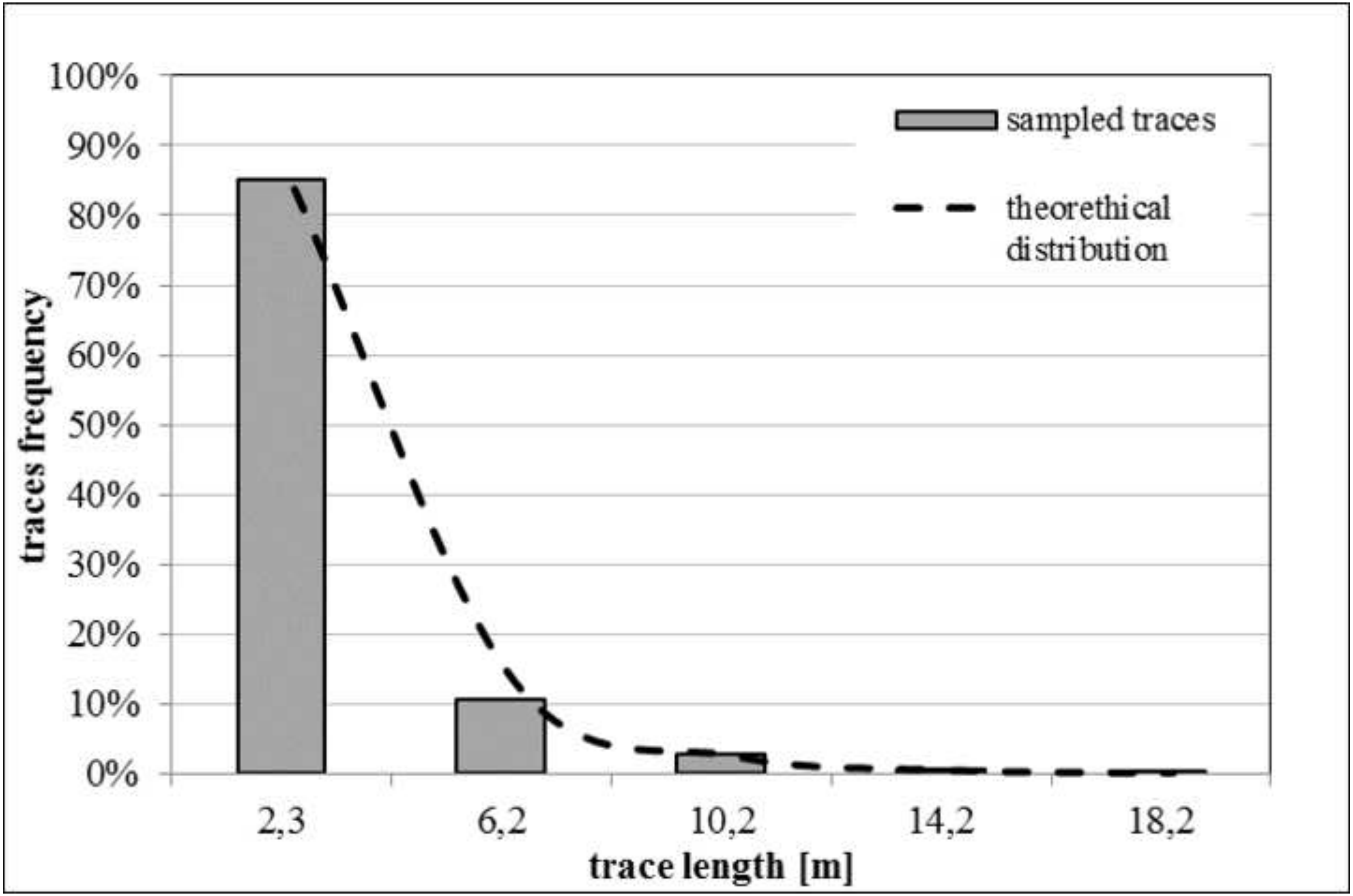
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
traces frequency
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2,3
6,2
10,2
14,2
18,2
trace length [m]

Figure 10

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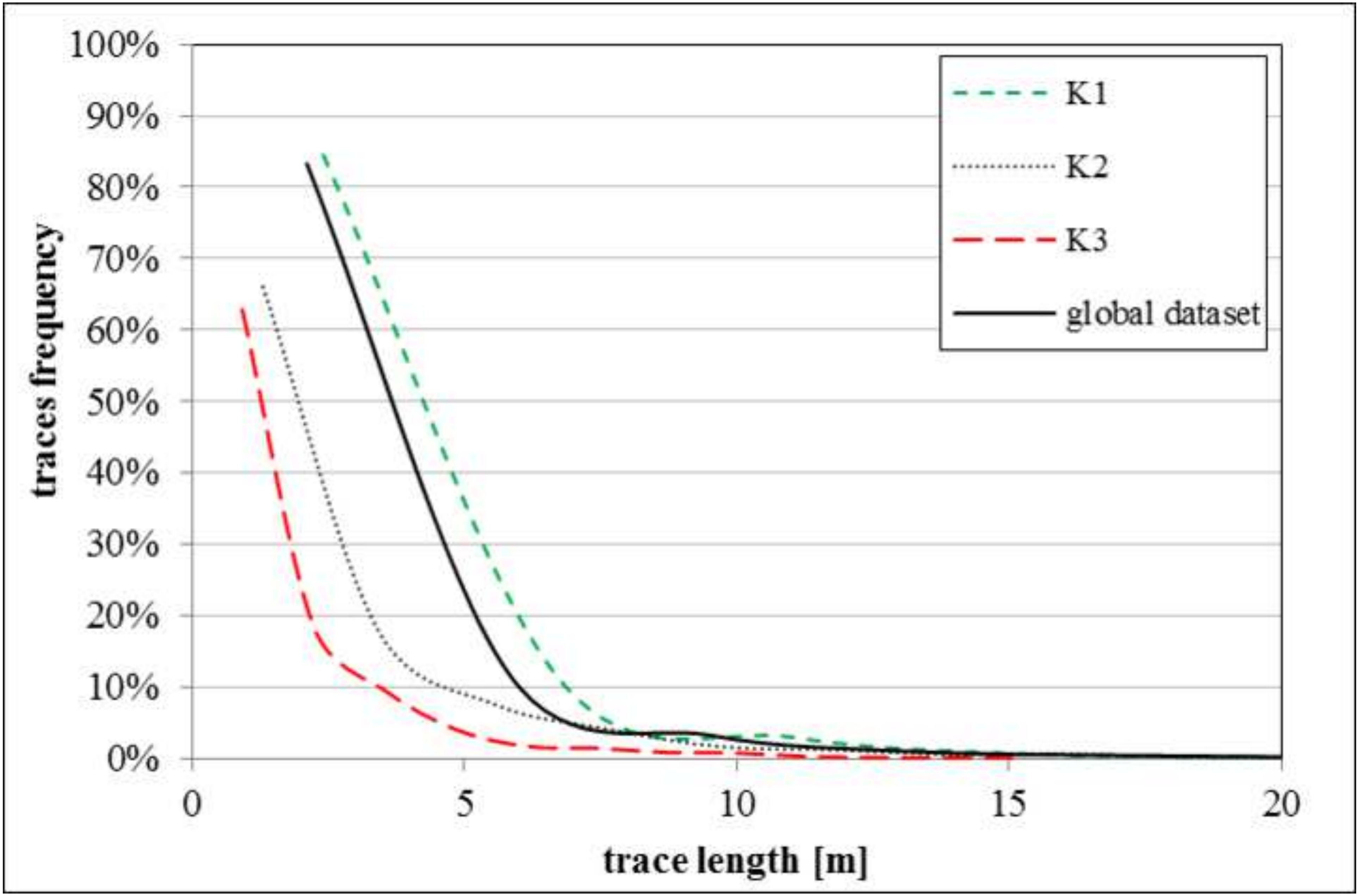

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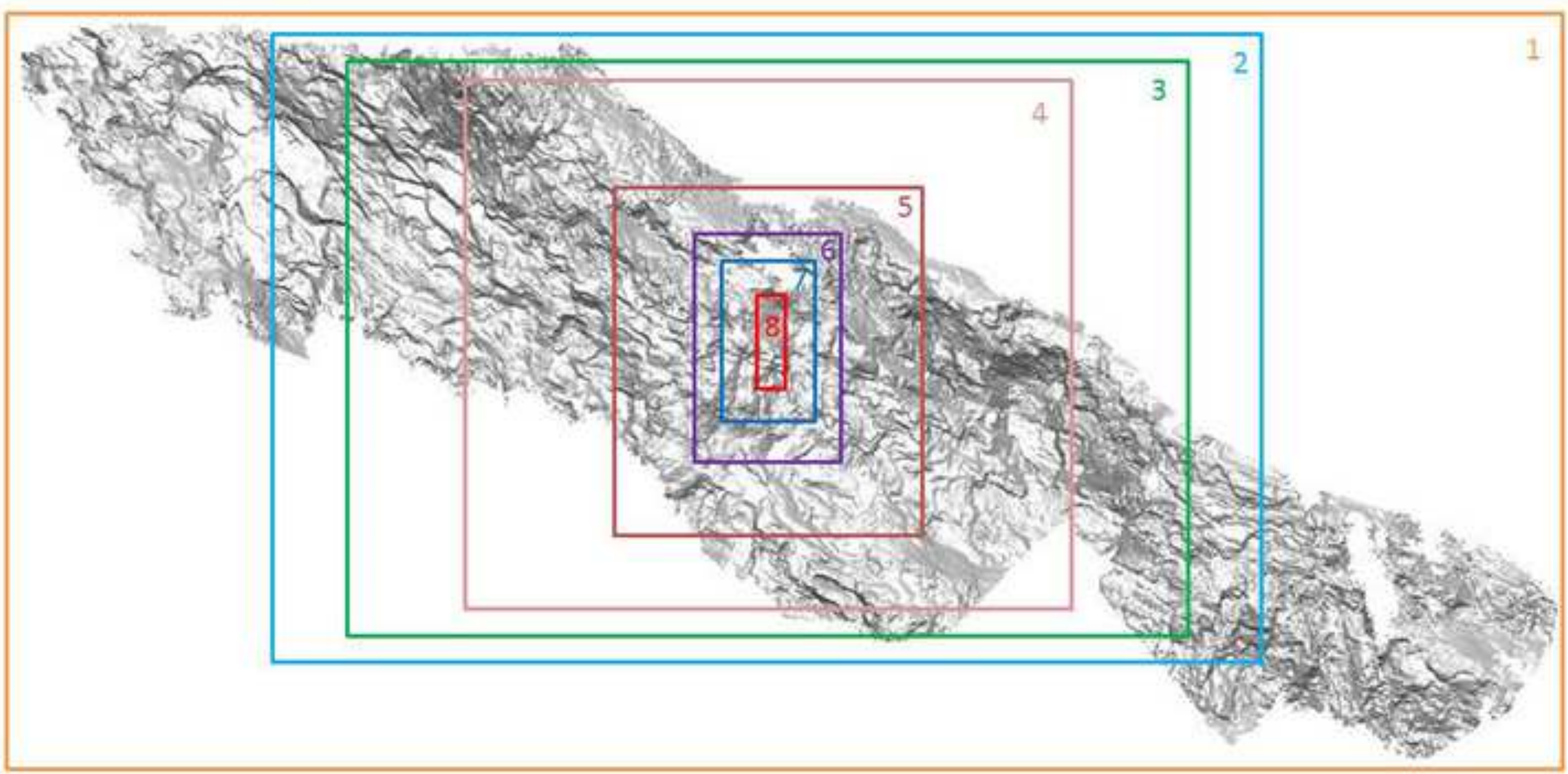

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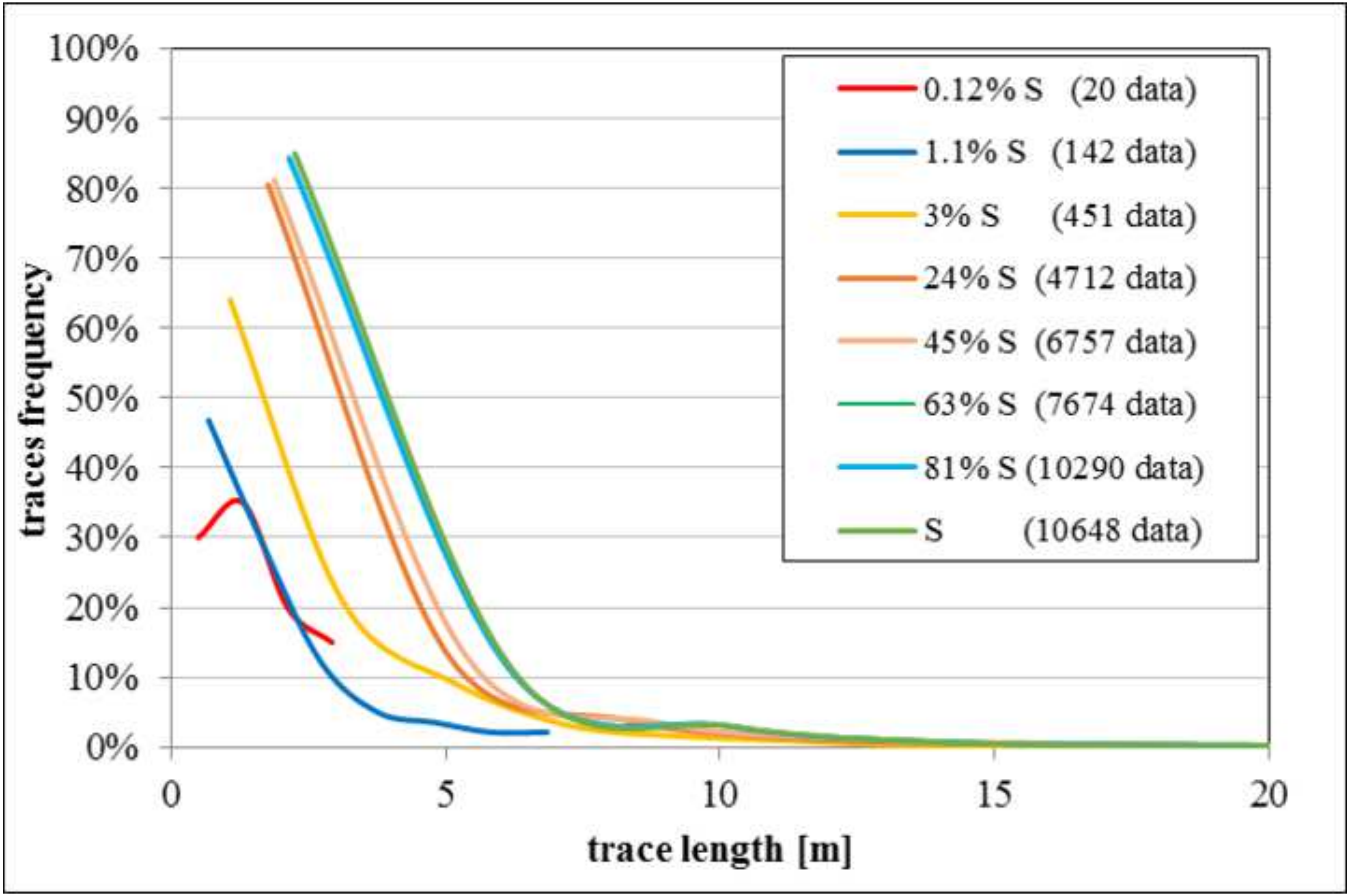

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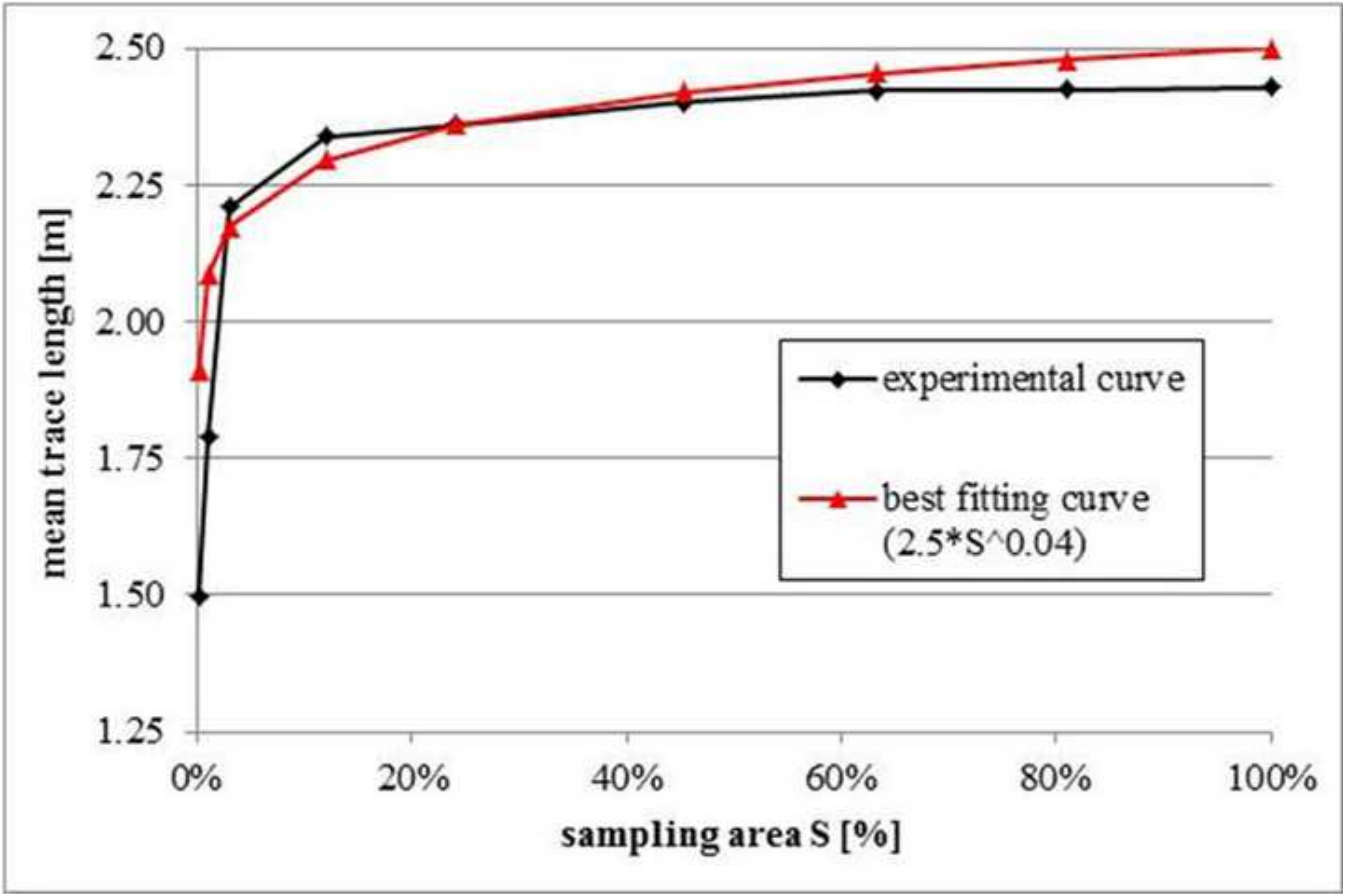

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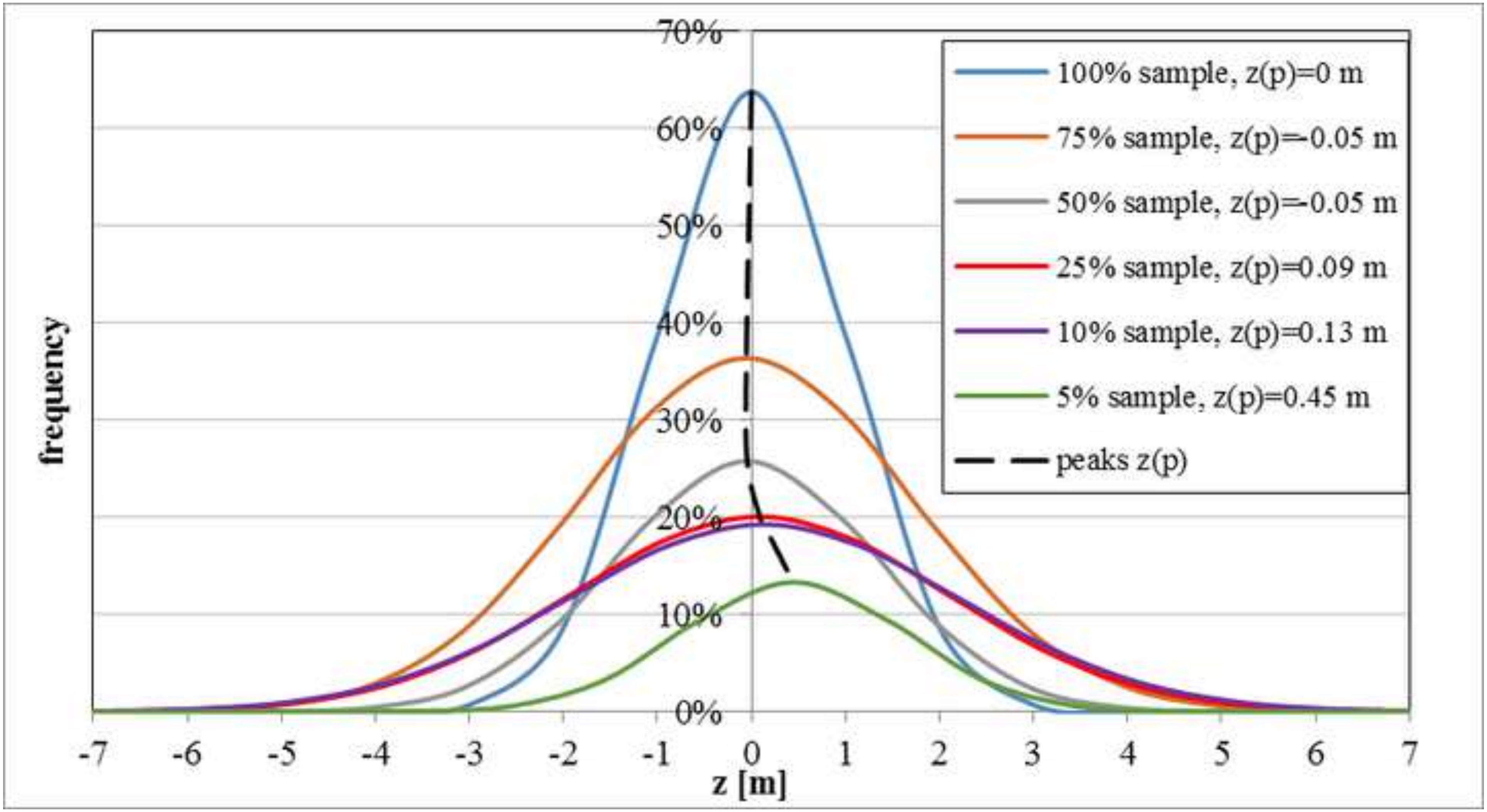

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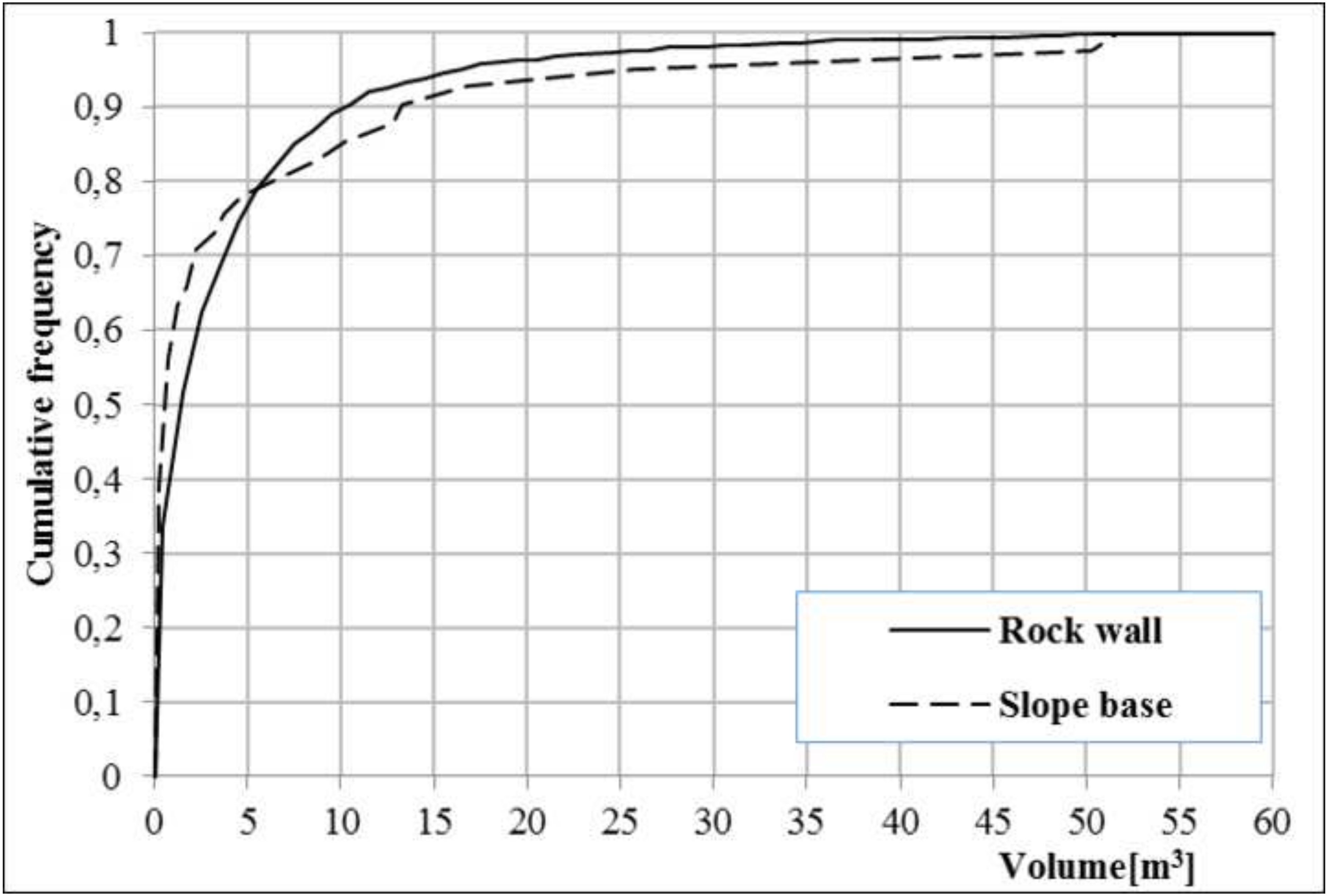
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0,4
0,3
0,2
0,1
0
Cumulative frequency
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15
20
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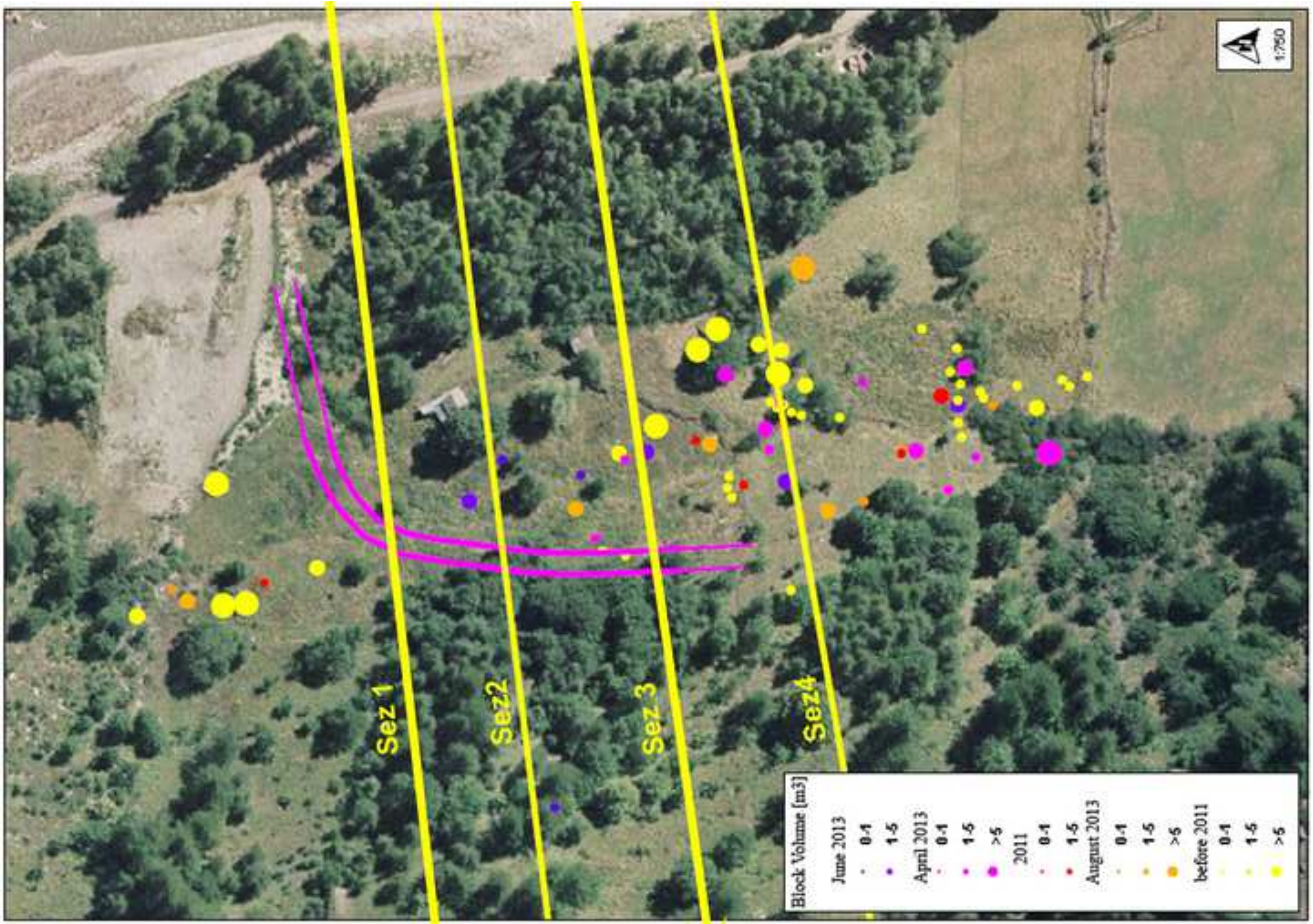
30
35
40
45
50
55
60
Volume[m3]
Rock wall
Slope base

Figure 16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Sez 1
Sez2
Sez 3
Sez4
Block Volume [m3]
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0-1
1-5
April 2013
0-1
1-5
>5
2011
0-1
1-5
August 2013
0-1
1-5
>5
before 2011
0-1
1-5
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Figure 17

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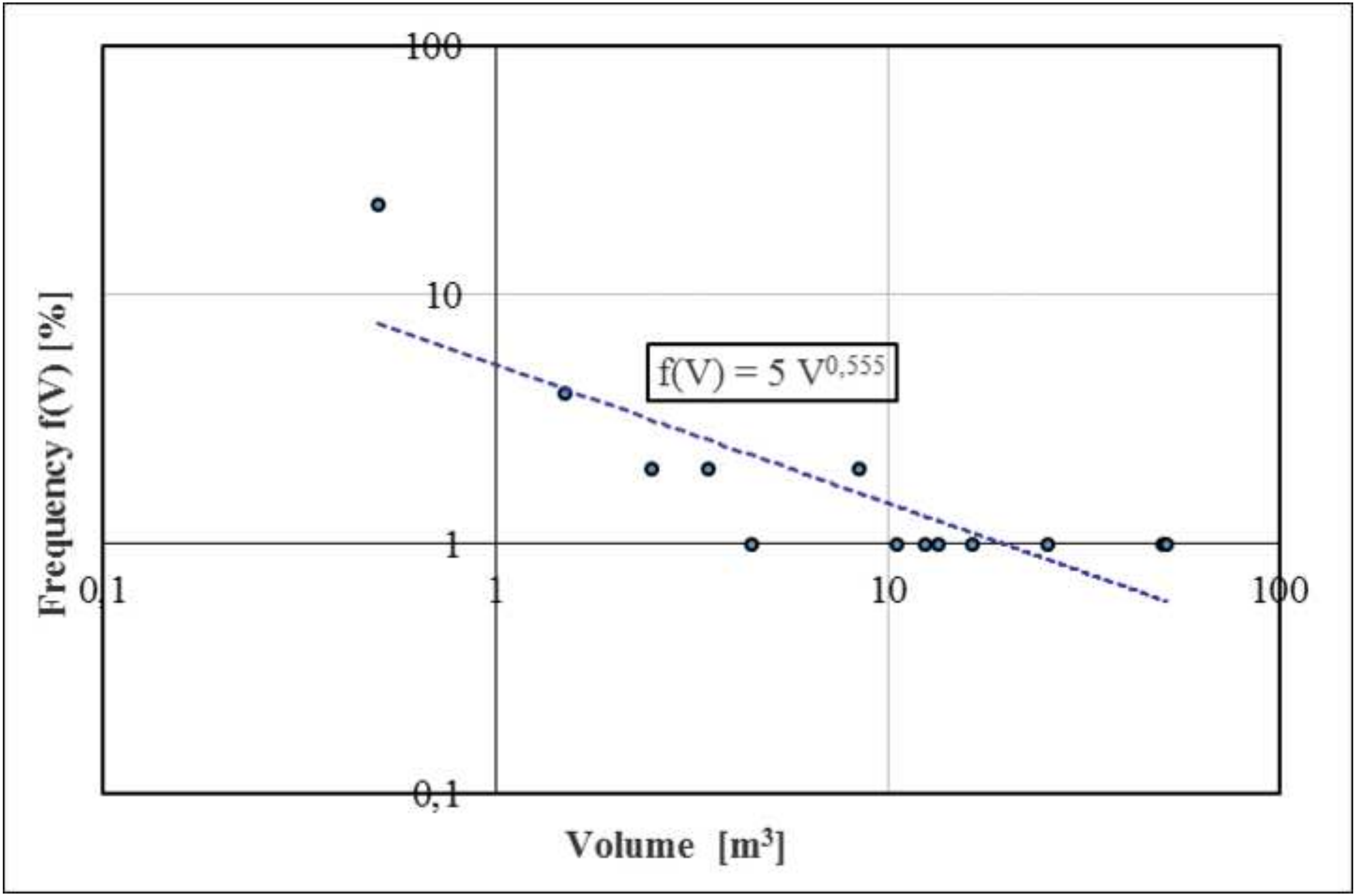

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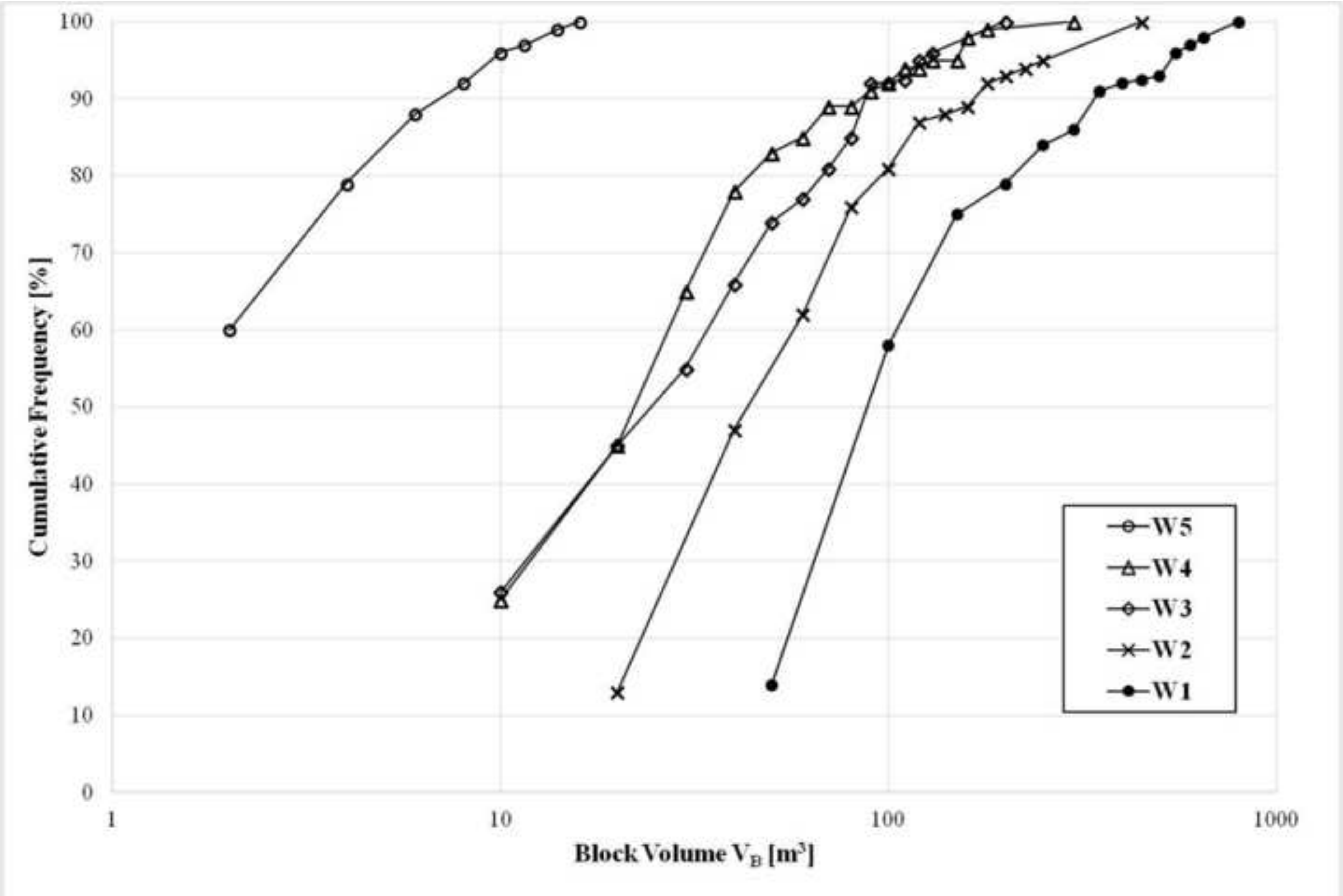

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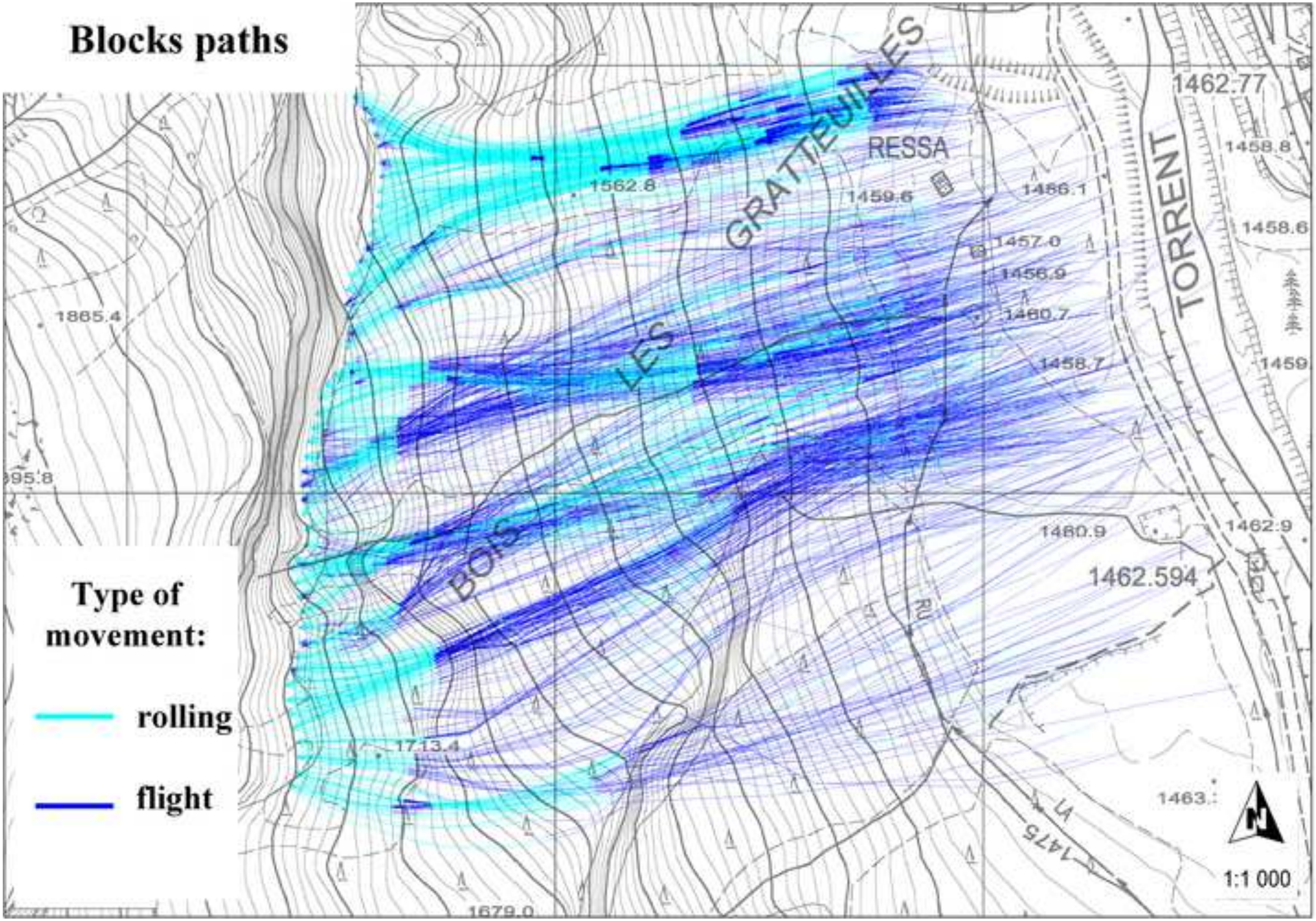

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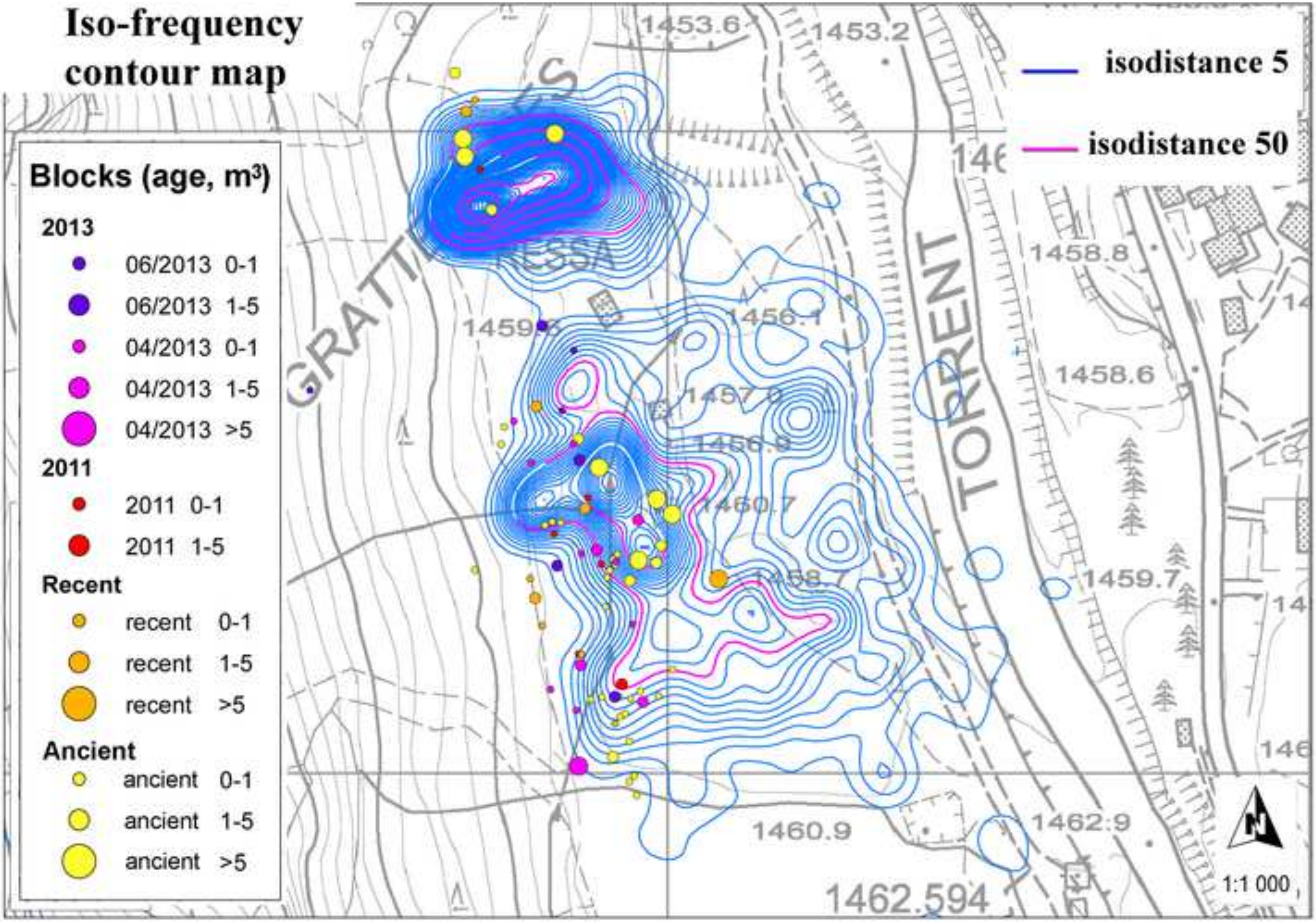

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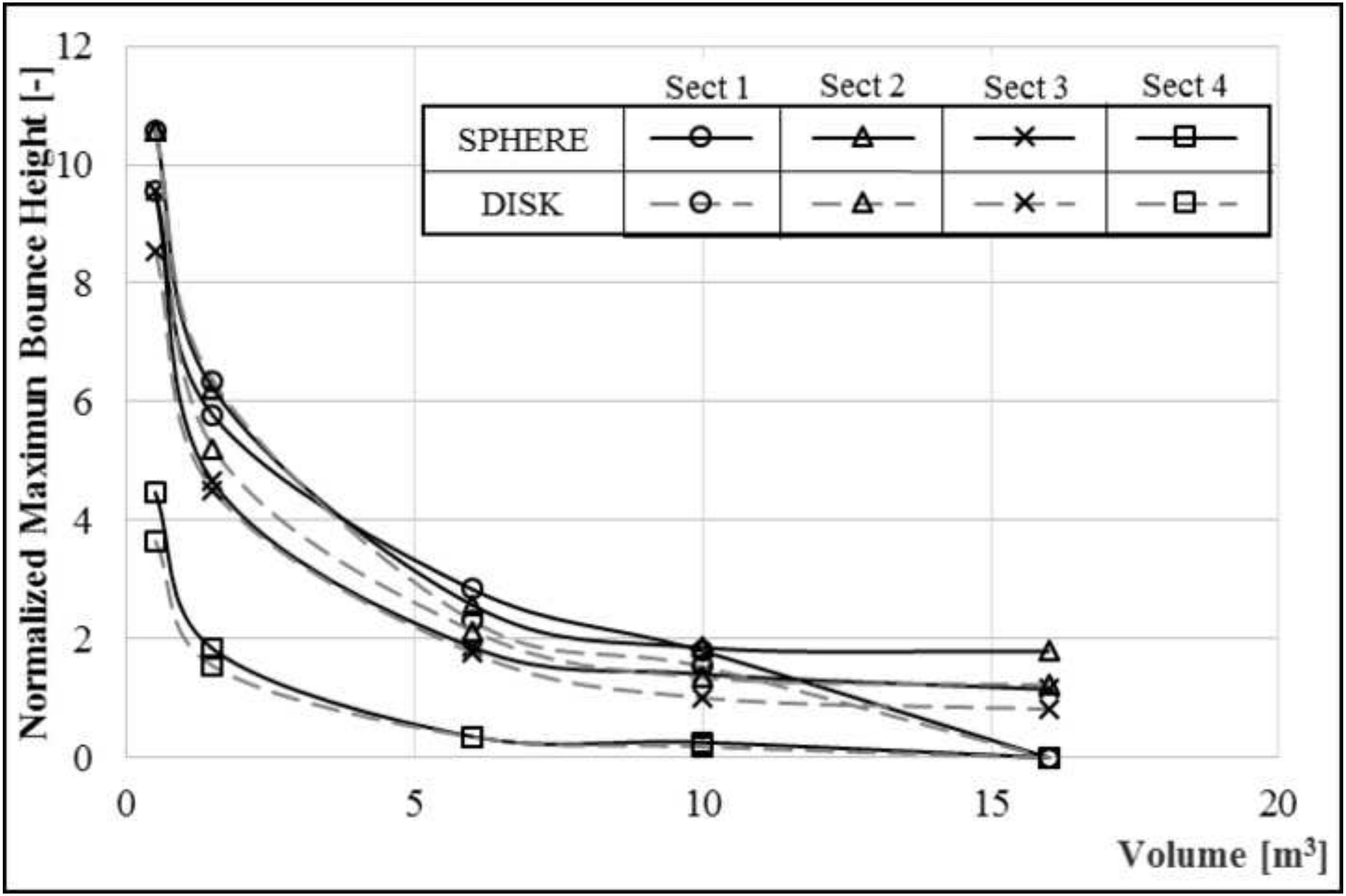

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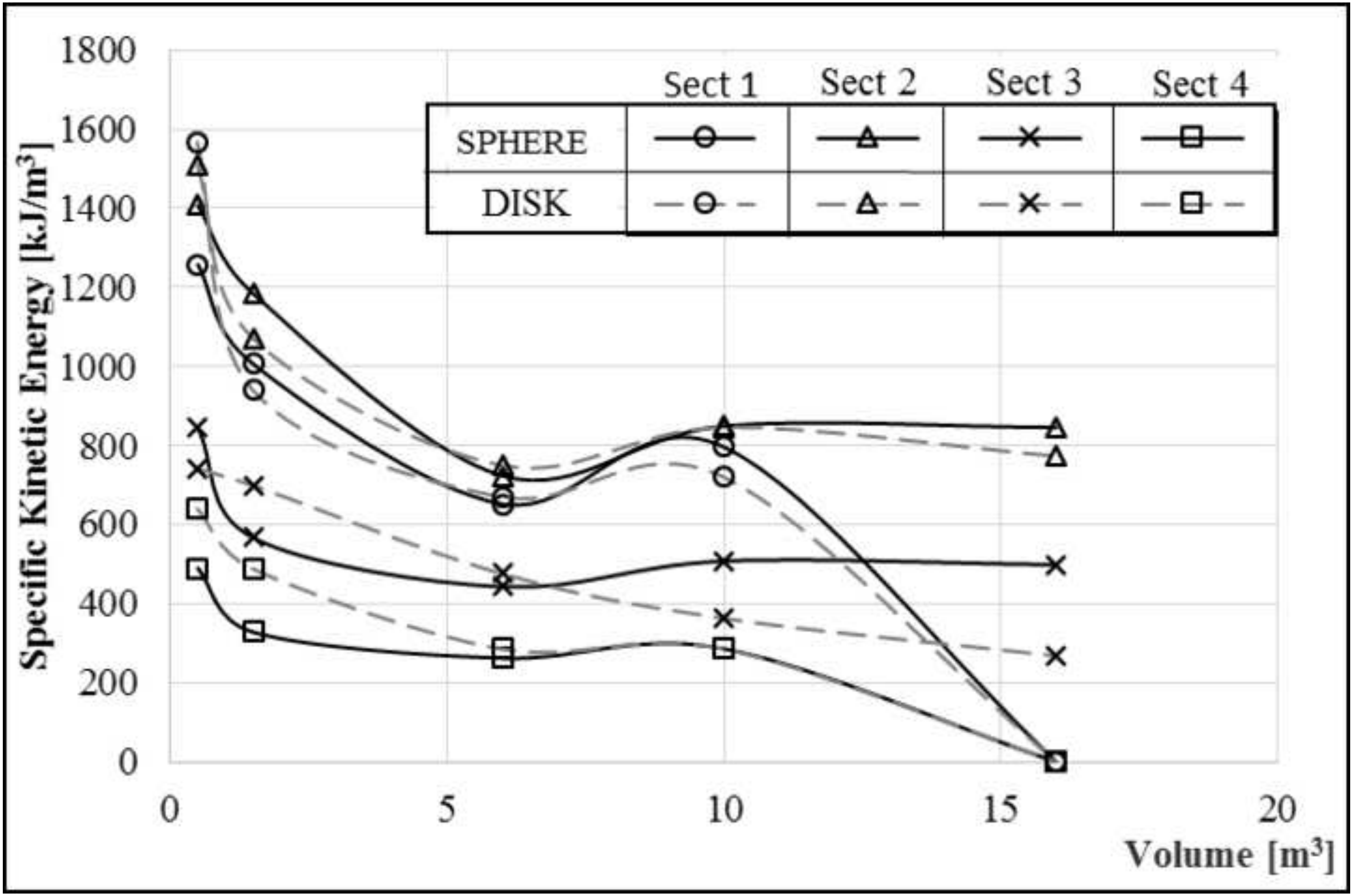

Table 1. Mean and standard deviation values of the trace length samples for each discontinuity set and for the global sample and parameters of the associated frequency distribution

	n° of traces in the sample	m_s [m]	sd_s [m]	μ Eq. 3 [m]	σ Eq. 4 [m]	T Eq. 6 [-]	$\chi^2_{\alpha,k-1}$ (α = 1%, κ=12)	Goodness of fit test is satisfied? Eq. 5
K1	3054	1.83	1.81	0.55	1.83	0.11	23.21	yes
K2	3854	2.57	2.91	0.39	2.57	0.10	23.21	yes
K3	3812	2.66	3.49	0.38	2.66	12.93	23.21	yes
global	10720	2.39	2.91	0.42	2.39	14.97	26.22	yes

Table 2. Mean and standard deviation values of spacing global sample and considered subsamples

	Percentage of sample					
	100%	75%	50%	25%	10%	5%
mean [m]	2.08	2.03	2.04	2.17	2.21	2.53
standard deviation [m]	1.76	1.75	1.39	1.99	2.07	1.20

Table 3. Tangential (R_T) and normal (R_N) restitution coefficients and surface roughness parameter S used in CRSP code to analyze the rock fall run out.

	R_T			R_N			S	
Volume [m^3]	0.5	1.5	6-10-16	0.5	1.5	6-10-16	0.5 – 1.5	6-10-16
Radius [m]	0.49	0.71	1.13-1.34-1.56	0.49	0.71	1.13-1.34-1.56	0.49-0.71	1.13-1.34-1.56
Outcropping rock mass	0.85	0.8	0.75	0.70	0.6	0.5	0.3	0.3
Debris with vegetation	0.65	0.6	0.55	0.35	0.3	0.25	0.4	0.5
Terracing at the base of the slope	0.6	0.5	0.4	0.3	0.25	0.2	0.6	0.7
Peat bog	0.4	0.3	0.2	0.25	0.2	0.15	0.3	0.3